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PSR J1016–5857: A YOUNG RADIO PULSAR WITH POSSIBLE SUPERNOVA REMNANT, X-RAY, AND γ-RAY ASSOCIATIONS

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ABSTRACT

We report the discovery of a young and energetic pulsar in the Parkes multibeam survey of the Galactic plane. PSR J1016–5857 has a rotation period of 107 ms and period derivative of 8.0×10^{-14}, implying a characteristic age of 21 kyr and spin-down luminosity of 2.6×10^{36} erg s^{-1}. The pulsar is located just outside, and possibly interacting with, the shell supernova remnant G284.3–1.8. Archival X-ray data show a source near the pulsar position which is consistent with emission from a pulsar wind nebula. The pulsar is also located inside the error box of the unidentified *EGRET* source 3EG J1013–5915, for which it represents a plausible counterpart.

Subject headings: ISM: individual (G284.3–1.8, 3EG J1013–5915) — pulsars: individual (PSR J1016–5857) — supernova remnants

1. INTRODUCTION

Observations of young rotation-powered pulsars offer unique opportunities to illuminate several fundamental questions about the physics of neutron stars and supernova remnants (SNRs). In particular, synchrotron emission from a pulsar wind nebula (PWN) can be used to determine properties of the relativistic pulsar wind, to probe the density of the ambient medium, and to study the evolution of SNR ejecta and their interaction with the local ISM. Confirmed associations between pulsars and SNRs also provide the opportunity to directly constrain the birth properties of neutron stars, including their space velocities and initial rotation periods. Such associations are often difficult to judge on the basis of the distance and age estimates for both objects, and a very powerful method of confirming an association is the observation of interaction between pulsar/PWN and SNR. However, young pulsars are rare, and cases where such interaction is apparent are rarer still.

One of the main aims of the Parkes multibeam survey of the Galactic plane (Manchester et al. 2001) is precisely to detect young pulsars, and at least ~ 30 of the 600 pulsars discovered to date are youthful, with characteristic age $\tau_c < 100$ kyr. Several of these are energetic as well (e.g., D'Amico et al. 2001). In this Letter we report on one such object, which archival radio, X-ray, and γ-ray observations suggest is remarkable.

2. RADIO PULSAR J1016–5857

PSR J1016–5857 was discovered in data acquired on 1999 March 15, collected in the course of the pulsar multibeam survey (Manchester et al. 2001) at the 64-m Parkes telescope in NSW, Australia. The pulsar has been the subject of regular timing observations at Parkes since 1999 May. These use the center beam of the multibeam receiver and the same data-acquisition system as the survey to collect total-power samples every 0.25 ms from 96 contiguous frequency channels between 1230 and 1518 MHz. The 1-bit digitized samples are written to tape for subsequent analysis, together with relevant telescope parameters, including the start time of the observation referred to the observatory time standard. The time on-source is 9 min on average each observing day.

The timing data are analyzed in standard fashion: samples from higher frequency channels are appropriately delayed to compensate for dispersion in the ionized interstellar medium. Data from all frequency channels are then summed and the resulting time series is folded modulo the predicted topocentric pulsar period to generate an average profile for each observation. A sum of several aligned average profiles yields the "standard profile" (Fig. 1), with which individual profiles are correlated to obtain times-of-arrival (TOAs).

The TOAs are analyzed with the TEMPO software package[8]: they are converted to the solar-system barycenter using the JPL DE200 planetary ephemeris (Standish 1990), and fitted to a Taylor series expansion of pulse phase by minimizing the weighted rms of timing residuals (observed minus computed phase). This yields precise values of pulsar rotation frequency ν, its derivative $\dot{\nu}$, and celestial coordinates. Many young pulsars, including PSR J1016–5857, experience rotational instabilities, and in the presence of such "timing noise" particular care must be taken in order to minimize contamination of fitted parameters. Following the prescription of Arzoumanian et al. (1994) we first "whiten" the timing residuals, by fitting for position, ν, $\dot{\nu}$, and higher frequency derivatives as required ($\ddot{\nu}$ in this case). The resulting celestial coordinates and uncertainties are our best estimates of these parameters and are listed in Table 1, as are ν and $\dot{\nu}$, which we determine from one additional fit with position held fixed and $\ddot{\nu}$ set to zero. We then

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[8]See http://pulsar.princeton.edu/tempo.

perform one final fit which includes $\ddot{\nu}$. This is *not* a term describing the secular evolution of the neutron star rotation, but results from rotational instability in the pulsar. In fact, both the sign and magnitude of $\ddot{\nu}$ strongly suggest that it mostly represents recovery from a glitch that occurred prior to the discovery of the pulsar (cf. Lyne 1996). The timing residuals corresponding to the solution presented in Table 1, based on 1.5 yr of data, are shown in Figure 1.

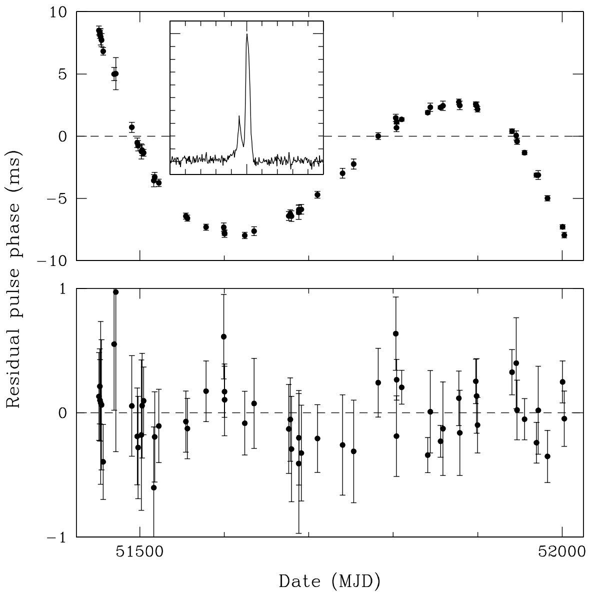

FIG. 1.— Pulse profile and post-fit timing residuals for PSR J1016–5857. Corresponding parameters and weighted rms residuals for "red" (top) and "white" (bottom) solutions are listed in Table 1. *Top: (inset)* average pulse profile at 1400 MHz, with 0.6 ms resolution. The full profile width at half the maximum intensity is w_{50} = 3.3 ms, and at 10% it is w_{10} = 11 ms; *(main)* fit for ν and $\dot{\nu}$ only (position held fixed at best fitted value). The quasi-cubic trend in residuals indicates presence of timing noise. *Bottom:* as for upper panel, with additional fit for $\ddot{\nu}$ (see § 2).

With period $P \equiv 1/\nu$ = 107 ms and a high $\dot{P}$, PSR J1016–5857's inferred characteristic age, $\tau_c = P/2\dot{P}$ = 21 kyr, is relatively small and its spin-down luminosity, $\dot{E} = 4\pi^2 I\dot{P}/P^3$ = 2.6×10^{36} erg s^{-1}, large. The surface dipole magnetic field strength is $B = 3.2 \times 10^{19}(P\dot{P})^{1/2} = 3.0 \times 10^{12}$ G (Table 1). These parameters make it similar to the small number of "Vela-like" pulsars, which have $\tau_c \sim 10^4$–10^5 yr and $\dot{E} > 10^{36}$ erg s^{-1}. Prior to the Parkes multibeam survey, only nine such pulsars were known. Thus far we have already doubled this number[9]. Pulsars in this group have high levels of glitch activity, and many are associated with PWNe and/or SNRs.

3. SUPERNOVA REMNANT G284.3–1.8

PSR J1016–5857 is located, at least in projection, near the supernova remnant G284.3–1.8 (MSH 10–5*3*; Milne et al. 1989; see Fig. 2). SNR G284.3–1.8 is an incomplete radio shell with non-thermal spectrum and with significant polarization, interacting with molecular clouds (Ruiz & May 1986). The pulsar is located exactly at the very tip of a "finger" of emission on the western edge of the remnant, and $\sim 15'$ from the SNR's approximate geometrical center.

In the Galactic plane, the spatial density of SNRs and pulsars is high, so the fact that a young pulsar lies near the edge of a SNR does not necessarily imply that they are associated: the probability of finding a pulsar lying by chance within $15'$ of a SNR center in this region of the Galaxy ($270° < l < 300°$) is about 5% (cf. Green 2000). However, the morphology of this particular pairing appears to bear a resemblance to that of PSR B1757–24 (another Vela-like pulsar) and its associated SNR G5.4–1.2 ("the Duck"). In the latter case, the pulsar has apparently caught up with, penetrated and overtaken the rim of its SNR, leaving a trail in its wake; the pulsar is now embedded in a ram-pressure confined (bow-shock) PWN (Manchester et al. 1991; Frail & Kulkarni 1991). Because of the limited resolution and sensitivity of the MOST data shown in Figure 2, it cannot yet be determined whether a similar association exists between PSR J1016–5857 and SNR G284.3–1.8. Nevertheless, the location of PSR J1016–5857 at the tip of a bright structure connected to G284.3–1.8 is suggestive of a physical association between the pulsar and SNR.

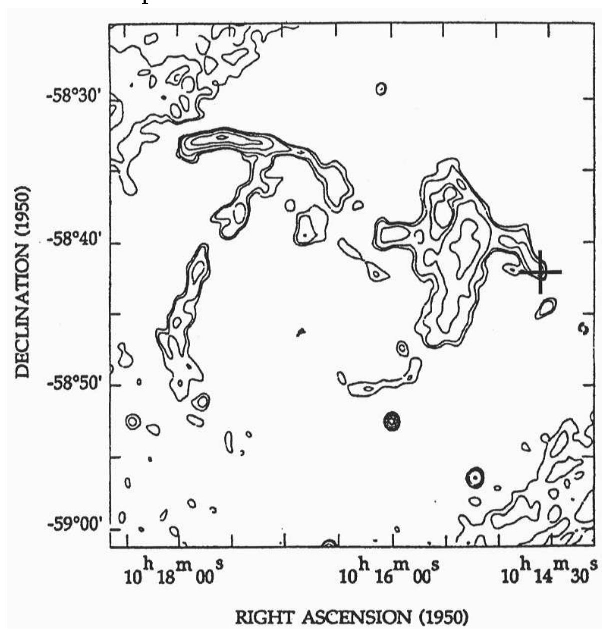

FIG. 2.— MOST radio map at 843 MHz of SNR G284.3–1.8 (Milne et al. 1989), with a spatial resolution of $45''$. The position of PSR J1016–5857, known with sub-arcsecond accuracy (Table 1), is indicated with a large cross at the tip of the protuberance on the western edge of the SNR.

If the pulsar and SNR are associated, the pulsar is at the distance of the SNR, d = 3 kpc, on the near side of the Carina spiral arm, as determined from optical and CO line observations with an uncertainty of only $\approx$ 20% (Ruiz & May 1986). This distance is smaller than that inferred from the pulsar's dispersion measure (DM) and a model for the free electron distribution in the Galaxy, $d = 9^{+3}_{-2}$ kpc (Taylor & Cordes 1993). However, the model is at its most uncertain along spiral arm tangents, the direction of PSR J1016–5857, so that the discrepancy may not be as serious as it appears. A similar example is provided by the recently discovered $\sim$ 1600-yr-old pulsar J1119–6127 (Camilo et al. 2000) and its clearly associated SNR G292.2–0.5 (Crawford et al. 2001; Pivovaroff et al. 2001), where the model puts the pulsar at $d > 30$ kpc, when in fact it lies at $d \lesssim 8$ kpc. Hypothesizing the PSR J1016–5857/SNR G284.3–1.8 association, we consider d = 3 kpc hereafter.

The age of G284.3–1.8 is estimated by Ruiz & May (1986) as $\sim$ 10 kyr, by fitting line profiles observed from an optical filament to models of interstellar radiative shocks. This

[9]See http://www.atnf.csiro.au/research/pulsar/pmsurv.

is similar to the pulsar's characteristic age, $\tau_c = 21$ kyr. However, pulsar characteristic ages are not necessarily accurate estimates of true age τ: e.g., in the B1757–24/G5.4–1.2 system, $\tau \gg \tau_c$ (Gaensler & Frail 2000), while for the pulsar in SNR G11.2–0.3, $\tau \ll \tau_c$ (Kaspi et al. 2001). Still, if the PSR J1016–5857/G284.3–1.8 association is real, and the age of the system is $\sim \tau_c$, we can estimate the velocity required for the pulsar to move ballistically from its putative birthplace (SNR center) to its present location: $v \sim 500(d/3\,\mathrm{kpc})(21\,\mathrm{kyr}/\tau)\,\mathrm{km\,s^{-1}}$. This velocity is within the range expected for young neutron stars (Lyne & Lorimer 1994), but is highly supersonic in the local ISM. A characteristic bow-shock PWN is then expected, as is observed for PSR B1757–24 (Gaensler & Frail 2000). Such a bow-shock nebula, of typical extent $\lesssim 1'$, could not be seen in Figure 2. Furthermore, the larger-scale finger connecting to the SNR need not point in the direction of motion, since the "wake" left behind by the pulsar can be distorted by ISM motions and turbulence. Finally, in comparing the PSR J1016–5857/G284.3–1.8 and PSR B1757–24/G5.4–1.2 systems, we note that the pulsars are uncannily alike: $P = 107/128$ ms, $\tau_c = 21/16$ kyr, $\dot{E} = 2.6/2.5 \times 10^{36}\,\mathrm{erg\,s^{-1}}$, $B = 3/4 \times 10^{12}$ G.

4. X-RAY OBSERVATIONS

Energetic young pulsars such as PSR J1016–5857 often produce detectable high-energy emission, especially if their distance is not too large (as we have argued in the previous section). A search of the HEASARC archive for serendipitous high-energy observations of PSR J1016–5857 has yielded one pointing at SNR G284.3–1.8, obtained with the Imaging Proportional Counter (IPC) on-board the *Einstein Observatory*. The IPC is sensitive to 0.1–4.5 keV X-rays over its $1^\circ \times 1^\circ$ field-of-view with an image resolution of $1'$–$3'$. The standard processed image from this 1.9 ks exposure (Seq. I5288), acquired on 1980 February 5, is shown in Figure 3. The pulsar position is near the center of the IPC field and coincides with an excess of localized X-ray emission, the most significant in the field. This emission is consistent, given the limited number of counts, with a point source, with possible extended emission. From the original event data files, we extracted 134 counts from a $r = 3'.0$ circle around the peak of emission and estimated the background counts within a surrounding annulus at $3'.2 < r < 6'.2$. The 45 background-subtracted counts yield a source significance of $4.8\,\sigma$ and a centroid which is $\sim 1'.8$ offset from the radio position. While much larger than the nominal *Einstein* pointing error ($\lesssim 10''$), this offset is consistent with the IPC instrumental measurement error and the small number statistics (e.g., Harris et al. 1990).

To estimate the luminosity of the source we assume a typical pulsar power-law model with photon index ≈ 2, as might be appropriate for magnetospheric emission or origin in a non-thermal nebula. A measure of the Galactic neutral hydrogen column density to the pulsar is estimated from the H I study of Dickey & Lockman (1990)[10]. This gives $N_H \approx 10^{22}\,\mathrm{cm^{-2}}$, consistent with the rule of thumb of 0.1 free electrons per H atom and the pulsar's DM. For isotropic emission, we obtain an unabsorbed X-ray luminosity of $L_{x,0.1-4.5\,\mathrm{kev}} \sim 10^{33}(d/3\,\mathrm{kpc})^2\,\mathrm{erg\,s^{-1}}$. This represents an efficiency for conversion of rotation-driven luminosity into X-rays of $L_x/\dot{E} \sim 5 \times 10^{-4}$ in the *Einstein* band. Such an efficiency for the point source and any compact nebula surrounding it is consistent within uncertainties with that observed for young pulsars (e.g., Seward & Wang 1988).

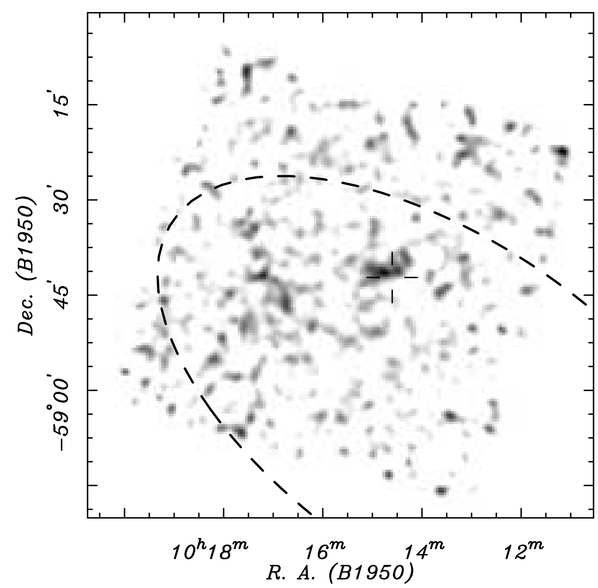

FIG. 3.— *Einstein* IPC observation of the PSR J1016–5857/SNR G284.3–1.8 field: a possibly extended source is detected near the position of the pulsar (cross-hairs; see § 4). The ellipse overlaid represents the approximate $2\,\sigma$ contour of positional uncertainty for the *EGRET* source 3EG J1013–5915 (Hartman et al. 1999; see § 5), which has an effective $2\,\sigma$ uncertainty radius $43'$.

Given the limitations of the detection, the origin of the observed emission is not certain at present. Possible contributions include emission from: a point source (e.g., pulsed magnetospheric emission); a compact nebula (bow-shock or static); the SNR; or even interaction of the SNR with a molecular cloud (cf. Ruiz & May 1986)[11]. However, the inferred flux is in excess of the thermal emission expected from a ~ 20 kyr-old neutron star for a reasonable N_H, while the measured flux is approximately as expected from a PWN in such a pulsar system. Also, if the extended emission is real, it appears to point back towards the center of the SNR, suggestive of a ram-pressure confined wind nebula.

5. γ-RAY SOURCE 3EG J1013–5915

As shown in Figure 3, PSR J1016–5857 and the *Einstein* X-ray source are within the $\approx 43'$ error box of *EGRET* source 3EG J1013–5915. This γ-ray source has flux $(3.3 \pm 0.6) \times 10^{-7}$ photons $\mathrm{cm^{-2}\,s^{-1}}$ (> 100 MeV), and photon index $\Gamma = 2.32 \pm 0.13$ (Hartman et al. 1999). This photon index is slightly larger than for most γ-ray pulsars, but consistent with those of the Crab ($\Gamma = 2.19$), and the Vela-like PSR J2229+6114 ($\Gamma = 2.24$), which is almost certainly the source of the γ-rays from 3EG J2227+6122 (Halpern et al. 2001). 3EG J1013–5915 is possibly a composite source (Hartman et al. 1999), in which case the photon index of any pulsar component may be differ-

[10] Accessible via the *nH* tool at http://heasarc.gsfc.nasa.gov/docs/corp/tools.html.

[11] Only one cataloged object exists within $2'$ of the pulsar position, the A2 star HD 302636, $1'$ away. If this star were a supergiant it would lie outside the Galaxy, while if it is a main-sequence A2V star it lies at $\lesssim 1$ kpc. At such a distance, the flux measured from the *Einstein* source would imply a luminosity in excess of that known for any A2V star.

ent from the nominal value, and its flux will be lower than that listed. The source is not obviously variable (McLaughlin et al. 1996), and the flux integrated from 100 MeV to 10 GeV with the nominal photon index corresponds to an isotropic luminosity $L_\gamma \sim 1.6 \times 10^{35}(d/3\,\mathrm{kpc})^2\,\mathrm{erg\,s^{-1}}$, or $\sim 0.06\dot{E}$.

The chance probability for superposition of a Vela-like pulsar and an *EGRET* error box in the Galactic plane is not negligible: in the 1500 square degrees covered by the Parkes multibeam survey, where there are about 10 Vela-like pulsars known, *EGRET* error boxes cover 24 square degrees or 1.6% (Hartman et al. 1999). The chance probability that at least one of those pulsars is aligned with one of the error boxes is therefore $1-(1-0.016)^{10} = 0.15$. The actual probability is somewhat smaller if one considers only non-variable *EGRET* sources, but it is nevertheless significant.

However, both $L_\gamma/\dot{E} \sim 0.06$ and $L_\gamma/L_x \sim 100$ are approximately as expected for a pulsar of the age and $\dot{E}$ of PSR J1016–5857 (e.g., Thompson et al. 1999, and Seward & Wang 1988), as is the lack of variability in γ-rays. Also, every pulsar with a value of $\dot{E}/d^2$ greater than that of PSR J1016–5857 has been detected in γ-rays (although the distances of PSR J1016–5857 as well as those of other pulsars are substantially uncertain). Altogether, this makes an association between PSR J1016–5857 and 3EG J1013–5915 possible and intriguing. The proof that 3EG J1013–5915 is the γ-ray counterpart of PSR J1016–5857 would come from the detection of γ-ray pulsations. This will be difficult with *EGRET* data, since the timing noise of the pulsar and the likelihood of glitches (§ 2) prevent the reliable backwards extrapolation of the ephemeris required to search for γ-ray pulsations.

6. DISCUSSION AND FUTURE WORK

We have discovered an energetic and youthful pulsar, apparently located just outside SNR G284.3–1.8. Based on its spin characteristics, PSR J1016–5857 belongs to the rare class of Vela-like pulsars, those with $\tau_c \sim 10^4$–10^5 yr and $\dot{E} > 10^{36}\,\mathrm{erg\,s^{-1}}$. These pulsars are of particular interest, as many are embedded in PWNe and are observed to be interacting with their SNRs. Additionally, such pulsars are very efficient at converting their spin-down luminosity into γ-rays, and form the majority of *EGRET* sources identified with pulsars.

We have argued, based on its positional coincidence with one notable feature in the SNR, that PSR J1016–5857 may be interacting with G284.3–1.8, and therefore that the two objects are physically associated. Further supporting this notion is the detection of an X-ray source nearby PSR J1016–5857 and the positionally coincident unidentified γ-ray source 3EG J1013–5915. The luminosities of both X- and γ-ray sources, if located at the distance of G284.3–1.8, are consistent with provenance from PSR J1016–5857.

Confirming this picture will require high-resolution radio and X-ray observations that show the proposed interaction between pulsar and SNR. If a bow-shock is detected, its detailed study may constrain the pulsar velocity, age, spin-evolution, and ambient medium (cf. Gaensler & Frail 2000; Olbert et al. 2001). Confirmation of the nature of the *EGRET* source may have to await future missions such as *GLAST*.

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TABLE 1
PARAMETERS OF PSR J1016–5857

Parameter	Value
R.A. (J2000)	$10^{h}16^{m}21\overset{s}{.}16(1)$
Decl. (J2000)	$-58^\circ 57' 12\overset{''}{.}1(1)$
Rotation frequency, ν (s^{-1})	9.31274229245(4)
Period, P (s)	0.1073797565311(5)
Frequency derivative, $\dot\nu$ (s^{-2})	$-6.991787(7) \times 10^{-12}$
Period derivative, $\dot P$	$8.061818(8) \times 10^{-14}$
Second frequency derivative, $\ddot\nu$ (s^{-3})[a]	$1.03(2) \times 10^{-22}$
Epoch (MJD)	51730.0
Dispersion measure, DM (cm^{-3} pc)	394.2(2)
Data span (MJD)	51451–52002
Rms timing residual (red/white) (ms)[b]	4.3/0.24
Flux density at 1400 MHz (mJy)	0.46(5)
Derived parameters:	
Galactic longitude, l (deg)	284.08
Galactic latitude, b (deg)	–1.88
Distance, d (kpc)[c]	3?
Characteristic age, τ_c (yr)	2.1×10^{4}
Spin-down luminosity, $\dot E$ (erg s^{-1})	2.6×10^{36}
Magnetic field strength, B (G)	3.0×10^{12}

NOTE.—Numbers in parentheses represent $1\,\sigma$ uncertainties in the least-significant digits quoted.

[a] fitted for separately (not a secular term) — see § 2.

[b] see Figure 1.

[c] see § 3.